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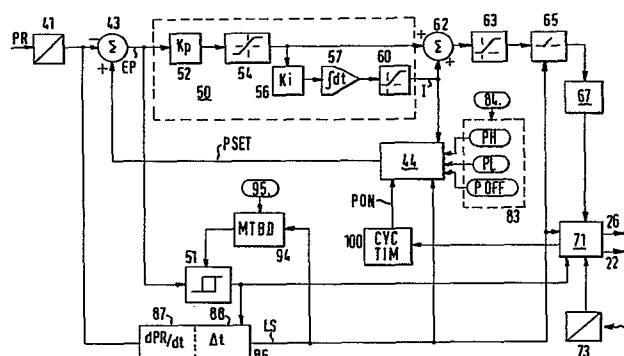
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⑤④ **Condition control system for heat transfer.**

⑤⑦ A condition control system for e.g. a boiler is responsive to a pressure (or temperature) signal PR to generate an on/off firing signal 22 and a firing rate signal 26, by a proportional control path (via 50) and an on/off path (51). The system operates in 2 modes: proportional (modulating), and cycling, determined by a limit switch signal LS. To minimize the cycling rate when cycling, the system is forced into the lowest fire rate when first fired up; the rate of change of pressure is sensed (at 86) and the signal LS changes the mode to proportional if the pressure falls (indicating that the low fire rate is inadequate). In the proportional mode, integral action (via 57) is used to adjust the setpoint PSET (via 44) to reach a stable operating state. In the cycling mode, the setpoint PSET is adjusted in dependence on the duty ratio of the cycles.



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CONDITION CONTROL SYSTEM FOR HEAT TRANSFER

The transfer of energy to and from a working fluid typically is accomplished under the control of a condition sensor such as a temperature or pressure responsive unit.

Ordinarily, the sensor measures a single condition of the working fluid and in turn controls the rate of transfer of energy to or from the working fluid in proportion to the deviation from a set point. This type of control system typically has a proportional offset, which is an offset from the desired setpoint or control point established for the operation of the system.

In many systems, there is a minimum or fixed lowest possible energy transfer rate for the system. Above that minimum rate, the system typically can modulate continuously to some fixed upper limit. There are often startup energy losses associated with the transition between a complete off state and the lowest operating rate, and incurred each time the system is caused to cycle.

The startup losses, and the operation of the system with a proportional offset, typically leads to certain inefficiencies. A more efficient manner of operating such a system can be brought about by minimizing the number of startup times for the system, and by tailoring the operation of the control so that the working fluid is not over heated or cooled but supplies just the minimum amount of energy required to satisfy a particular load.

The specific system that will be described herein is a boiler supplying steam to a steam heated load in response to a fuel burner control system. However, the invention is applicable to any system that controls the transfer of energy to and from a working fluid in a similar manner, such as a boiler operated merely to heat water, as opposed to generating steam. It could also be applied to air conditioning systems in which the working fluid is a heat transfer fluid other than water, or to a condition control system in

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which the working fluid is air which transfers heat or cold from a heat exchanger to a load to which the working fluid is applied.

According to the present invention there is provided a control system for a boiler or the like wherein an on/off control signal and a proportional control signal are generated in response to a sensed condition value, characterized by mode control circuitry, which, when the system is in the cycling mode, holds the firing rate of the boiler to the lowest rate, and changes the mode to proportional (modulating) if the sensed condition value falls while in the cycling mode.

It will be seen that the present system, in addition to reducing the number of start-ups, also increases the general efficiency of the boiler operation.

A control system embodying the invention will now be described, by way of example, with reference to the drawings, in which:

Figure 1 is a prior art system,

Figure 2 is an operating diagram of the Figure 1 system, and

Figure 3 is the present system.

PRIOR ART

Figure 1 shows a conventional steam pressure control which controls the firing rate of a boiler. Steam pressure PR is the sensed parameter, but temperature could equally well be sensed.

An upper signal path from a sensor 10 to a condition control sequencer 20 is a proportional path. A lower path from a sensor 10' to the sequencer 20 is an on/off control path. The two sensors 10 and 10' are typically distinct. The upper sensor 10 is a proportional sensor which produces an output signal in proportion to the sensed pressure. The other sensor 10' produces a discrete output indicating that the pressure level has risen above or fallen below a preset level. The sequencer means 20 coordinates the operation of the proportional and the on/off control circuits. When the

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sequencer means 20 receives the signal to turn on an associated burner, it initiates a sequence of safety related actions intended to safely light a burner flame. This sequence includes purging of the combustion chamber of accumulated unburnt fuels, lighting a pilot flame, checking the pilot flame to make sure it is actually lighted, and lighting up the main flame or burner. After the main flame is successfully ignited, the signal from the proportional control path controls the flow of fuel through a valve directly in proportion to a pressure error signal.

The functional elements shown in the proportional path originating with the sensor 10 are typically all integrated into an electromechanical sensor. The sensed pressure is differenced at 13 with the proportional setpoint SP-PR, yielding an error signal which passes through an adjustable electronic gain means 15. The mechanical limitations of the sensing element (typically a potentiometer) impose limits on the error signal as indicated at 17. Typically the error signal would be considered as ranging from 0 to 1, corresponding respectively to the lowest and highest firing rates, LF and HF, that can be continuously sustained by a conventional burner. This signal controls the sequencer 20 via a variable resistance 19. The proportional signal resulting from the sensor 10 is in effect a servo command that drives a servo motor 26 attached to the fuel valve. Commonly the pressure, through a mechanical linkage, drives a potentiometer wiper to produce a variable resistance within the sensor which is proportional to the pressure difference from unit 13. This variable resistance is connected in a bridge circuit which controls the operation of the servo motor. The servo motor moves the fuel valve to position it between its highest and lowest flow positions in proportion to the pressure error from unit 13.

The output of sensor 10' is differenced at 13' with an on/off setpoint SP-ON/OFF in the on/off control path to produce a proportional error signal which is converted to an

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on/off switched state by a hysteresis unit 18. When the error from 13' falls below a predetermined make level, the system switches from the off state to the on state. When the pressure rises to a higher predetermined break level, the hysteresis unit 18 switches back from on to off. The differential between the make level and the break level of the hysteresis block 18 is analogous to the proportional gain in the proportional control loop.

The proportional control plus on/off control function is a conventional system to drive the sequencer 20 to in turn control a burner in an on/off command mode, and then allow the system to modulate from the low fire position of the burner to the high fire position of the burner.

The proportional control signal from sensor 10' drives, via sequencer 20, an on/off fuel valve 22 in a fuel passage 23 that supplies fuel to a modulating fuel valve 24 that is controlled by a servo motor 26, which also drives an air damper 29 that supplies the burner air for the fuel burner. The on/off control circuit operates the sequencer means 20 to light a flame or to extinguish it. The sequencer means 20 in turn coordinates the purge, light up, and fire sequencing of the burner to which the system is connected. When the pilot light of the burner for the boiler is proved, the sequencer 20 opens the on/off fuel valve 22. Once the main flame is safely established, the sequencer 20 provides a proportional control signal from the proportional control circuit 17 to the servo motor 26, which in turn controls the modulating fuel valve 24 and damper 29 to properly supply air at the rate controlled by the modulating fuel valve 24.

Figure 2 is an operating graph for the control system of Figure 1. The vertical axis is the commanded firing rate FR of a burner with the high fire or maximum rate HF, the low fire or lowest sustainable rate LF, and the off or standby rate OFF positions noted. The horizontal axis ΔRP is the error from the setpoint in pressure (or temperature,

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depending on the type of application of the system). Point 31' on the error axis is the make point; the pressure must fall to this point in order to begin a firing cycle. When this happens, the sequencer 20 initiates the purge and safe light up procedure for the associated burner. This procedure then commands the high fire fuel and combustion airflow to the burner. As pressure rises in the associated boiler, the highest firing rate is reached at point 31 and maintained until a pressure point 32 is reached. As the pressure rises above the point 32, to a further point 33, the modulating or servo motor 26 closes the modulating valve 24 and reduces the airflow at damper 29. This operation drives the firing rate from a high firing rate down to a low firing rate at point 33. If the pressure within the boiler continues to rise beyond the point 33, a point 34 is reached, corresponding to a break or off point 34' on the error axis for the burner. If the pressure rises above the point 34, the fire is shut off and the pressure begins dropping from point 34' towards the make point 31'. If the heat load imposed on the boiler requires a higher firing rate than the low fire position, the system will remain in the modulating range between the points 32 and 33 and will not cycle in an on and off fashion. If the heat load imposed on the boiler is less than the low firing rate commanded for the system, the boiler must cycle in an on and off fashion since the fuel valve 24 cannot be closed to a firing rate lower than the low fire position.

With this control configuration, the boiler will always light up and commence firing at the highest firing rate possible even under light load conditions. If it were possible to prevent the high firing rate under light load conditions, each on/off cycle would be longer, causing the boiler operation to be more efficient. This efficiency improvement comes about because the on/off cycling loses energy due to the prepurge and postpurge operation of the sequencer 20 and its associated burner. If the high fire were prevented,

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the boiler would stay on for a longer period of time, servicing a greater load between each purge cycle. In this way more energy would be delivered per unit of energy lost to the purge process. The present system prevents a high fire operation by locking the boiler in the low fire mode after lighting up. The burner must remain in low fire for a predetermined interval, and the direction of change of pressure with respect to time is measured. If the pressure is rising while the burner is locked in low fire it is safe to conclude that the load imposed on the boiler is less than the low firing rate. Under these conditions the pressure will eventually rise to a break point and force the boiler off. Thus, it is not necessary to release the burner from the low firing rate during the cycle. If however, the pressure is falling after light up with the burner locked in the low firing rate, then the load on the boiler must be higher than the low firing rate. Under these conditions it will be necessary to release the control of the burner to the proportional path between points 32 and 33, which can then raise the firing rate as needed to match the load.

Attempts have been made in the past to prevent unnecessary high firing rates during cycling operation through the use of a lockout timer. The timer prevents higher than low fire firing rates for a fixed time interval after lighting up of the burner. The difficulty with this is that if the load is close to the low fire firing rate, a relatively short lockout time is insufficient to prevent the control system from commanding higher firing rates after the timer times out; but, if the lockout interval is made long enough to accommodate even very long on periods, the responsiveness of the control system to rapidly changing loads is compromised. That is, if the boiler is forced to remain in low fire for a long period of time and the load rises abruptly during that interval, the system will be unable to respond to the load increase, thus causing a significant drop in the pressure from the control point. The present system

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overcomes this problem since the rate of change of pressure is measured essentially continuously and the boiler will be released to the high firing rate whenever the pressure begins to fall. In this way, a rapid increase in load is detected essentially instantaneously and a higher firing rate is commanded before a significant pressure drop occurs.

Conventional burner and boiler controls operate in an on/off cycling mode under light loads and in a proportional mode at higher loads. When the boiler is modulating in the proportional control mode, the boiler pressure remains somewhat offset from the setpoint due to the phenomenon known as proportional offset. The mechanism which causes this problem can be seen in Figure 2. When the load is high, the pressure must fall toward the beginning of the modulating range (point 32) to cause the firing rate to be increased. When the load is low, the pressure rises towards the point 33, which reduces the firing rate and causes the load and the firing rate to come in balance with each other. This migration of pressure with load is called the proportional offset. The gain of the system determines the magnitude of the offset. The gain of the system is the slope of the firing rate versus the error plot on Figure 2. This is the slope between the points 32 and 33. With a very high gain (a steep slope) the variation in pressure required to cause a large change in firing rate is small. Hence, the offset in the pressure is small. This higher gain also leads to instability. Thus, with practical gain settings the pressure or temperature in the boiler is highest under light loads and lowest under high loads. This is just opposite the desired condition for maximum efficiency in the boiler operation.

A more efficient operating mode would be to have higher steam pressure or higher temperature when the loads are highest, and a lower steam pressure or temperature when the loads are low. In this way the boiler internal temperature will be as low as possible under each loading condition.

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To see how maintaining the lowest possible temperature yields the highest operating efficiency, a typical boiler construction should be considered. Fuel is burned in a chamber called a fire box giving up some of its heat to the surrounding water. The combustion products pass through the boiler's heat exchanger (which is made up of a number of small tubes) where heat is removed, bringing the combustion products downward in temperature until they leave the boiler; any remaining heat is lost up the flue. The cooler the boiler water temperature, the lower will be the temperature of the existing combustion products. In this way the lower operating temperature yields higher efficiency.

In most applications, the boiler setpoint is higher than necessary to service the loads. The heat from the condensing steam is transferred to the end use via a heat exchanger. The heat exchangers are typically sized to handle the load on the system with a reasonable temperature drop from the steam temperature to the end use load temperature. To control the rate at which heat is delivered to the load, a local loop control is often employed. This control senses the temperature at the load to be controlled, and adjusts the steam flow rate to the heat exchanger to maintain the desired condition. A control valve causes the steam at the load to be at a lower pressure, and hence, a lower temperature than it was generated at in the boiler. Thus at light loads, the boiler temperature is often higher than the actual temperature at which heat is being delivered from the steam at the load. Under these light load conditions, it would be desirable to reduce the boiler setpoint, making the boiler operate more efficiently because the loads can be satisfied with lower temperature steam. Under high load conditions, it would be necessary to raise the boiler setpoint so that the required temperature drop from the steam to the end load is available at the heat exchanger to guarantee the higher heat flow rates required. The present system adjusts the boiler setpoint automatically with boiler load. The key to

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this process is the ability of the controller to sense the total load on the boiler.

THE PRESENT SYSTEM

5 Before describing the present system in detail, two concepts that are utilized in it will be discussed and their operation described.

10 Burners for boilers operate in two modes. There is an on/off cycling mode and a modulating mode. In each mode of operation the present system is able to sense the net imposed heat load on the boiler, and reset the setpoint of the system according to the load. Under light load conditions, when the boiler must cycle on and off, the present system locks the firing rate at its lowest level. Under these conditions, the imposed load on the boiler can be determined
15 by timing the duration of the on and off cycles. The ratio of the on time to the sum of the on and off times is equal to the ratio of the load on the boiler to the boiler's capacity with the burner at low fire. The present system (in cycling operation) measures the half cycle times and computes the load using the above relationship. The load is in
20 turn used to reset the setpoint of the system. Manual adjustment is possible. The operator can prescribe a setpoint to be associated with loads at the lowest firing rate. The operator also can adjust a setpoint associated with the
25 standby or zero load condition. The device automatically senses the magnitude of the load between the zero and the low fire sensing rate, and adjusts the setpoint between the two manual input setpoints.

30 When the load on the boiler is greater than the low firing rate, on/off cycling should not occur. Under these conditions, the present system adjusts the firing rate via the conventional proportional control path to match the firing rate with the imposed load. Under steady state conditions, the proportional control path leaves a proportional
35 offset in pressure between the sensed pressure and the desired setpoint. When the loads are low, the offset is also

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low. When the loads are highest, the proportional offset is equal to the modulating range of the control system. That modulating range is the distance on the pressure axis of the graph of Figure 1 between the points 32' and 33'. It is well understood that a simple proportional control device can be improved with the application of a technique commonly known as integral action. With this technique the steady state proportional offset can be eliminated. The technique is to pass the error signal in the proportional control path through an integrator. The integrated pressure error signal is added to the proportional control signal. This technique drives the sensed error signal to zero as the integral of the error signal rises to a level such that the integral output alone commands the required firing rate to maintain the setpoint without offset. In equilibrium, the proportional control has zero output and the integral control determines the firing rate. The integrator output in steady state is equal to the proportional offset that would have occurred had integral action not been employed. In this way the integral output just cancels the proportional offset.

The integral output is also a measure of the load on the system. This is critical to the present system, as the integral output is used in the present system for a specific control purpose. The ratio of integral output to the magnitude of the modulating range is equal to the load imposed on the boiler divided by the difference between the high firing rate and the low firing rate. Thus, the integral output is a direct measure of where the load level is relative to the highest and lowest firing rates. Thus, the integral output can be used to reset the setpoint of the control system when it is operating in the modulating mode.

Figure 3 is a block diagram of the present system. Steam pressure PR is applied to a sensor 41 which feeds a differencing means 43 also fed with a signal PSET, from a setpoint means 44, which is a modified setpoint for the

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system. The output of the differencing means 43 is a signal EP which is the preliminary error signal for the system. This signal EP is fed to an error signal processing means 50, and also to an on/off error detection means 51. The circuitry 50 generates a proportional signal in the system, while the circuitry 51 provides an on/off switching action.

In the circuitry 50, signal EP is fed to a gain element 52, which can be of any type, and typically would be adjustable to make the system applicable to different types of condition control systems. Element 52 feeds a signal limiter 54 that limits the preliminary error signal EP to a range of between -1 and +1. The limiter 54 feeds a further gain element 56 which in turn feeds an integrator 57 the output of which is limited by a limiter 60 to a signal I within a range of 0 to +1.

A summer 62 sums the outputs of limiters 54 and 60, and its output is in turn limited by a limiter 63 to a range of 0 to +1. The output of limiter 63 is fed via a gate 65 to a converter 67 which converts the signal to a varying resistance value which drives a sequencer 71. Thus control is of a modulating or proportional type. The sequencer 71 controls the servo motor 26 of Figure 1. A typical burner control system has a flame detector 73 to supply information back to the sequencer 71, which is also fed with a signal LS, which is an on/off type of command.

The setpoint means 44 has two different operating modes and is fed by adjustable input means 83, 84. The adjustable or manual input means PH is used to set the operating pressure for the device at its highest fire rate. The manual input adjusting means PL is used to establish the pressure at the low fire rate. A third manual setpoint input POFF is provided to set the off position or quiescent normal state for the boiler when it is not supplying a load, but when it is ready to be activated. All the setpoint means PH, PL and POFF can be combined at 83 into a single setpoint member that is controlled by knob 84 that sets all three

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elements into the setpoint means 44 at the same time. The three setpoint values are all definite pressure levels that must be set into the system for its proper operation. The setpoint means 44 sets the setpoint pressure PSET in dependence on the logic level of signal LS, thus:

$$\begin{aligned} \text{PSET} &= \text{PL} + (\text{PH} - \text{PL})\text{I} && \text{if LS} = 0. \\ &= \text{POFF} + (\text{PL} - \text{POFF})\text{PON} && \text{if LS} = 1. \end{aligned}$$

The sensor 41 also feeds a load responsive circuit 86 which performs two successive functions. The first function is to sense the pressure from the sensor 41 and determine whether the pressure is rising or falling. This pressure direction sensing is accomplished at 87 by a differentiation of the signal or by a simple comparison of short time intervals to determine whether the pressure is rising or falling. The second function is to provide at 88 a time delay, which is necessary to prevent the system from improperly responding during transient conditions, such as the startup of the burner when the pressure in the boiler might not be responding directly to the action of the burner applied to the boiler. The load responsive circuit 86 produces the limit switch signal LS which is fed to three units: the gate 65, thereby determining whether or not the sequencer command signal is to pass from 63 to 67; the setpoint means 44; and a make to break differential device 94. The limit switch signal LS is a logic signal 1 when the system is locked or operating in the low fire condition, and 0 when the system is operating in a modulating manner. Thus the limit switch signal LS determines which of the two modes of operation the system operates in.

The make to break differential means 94 has a manual input 95 that establishes a manual make to break differential. The output signal is equal to the manual input if signal LS is 1, and is only 40% of the manual input if signal LS is 0. This results in more stable operation, as will be explained later. The make to break differential means 94 feeds the on/off error detection means 51 and establishes

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the magnitude of the signal from unit 43 at which the on/off error detection means 51 will switch its output. This output is coupled directly (or via the sequencer 71) to the load responsive circuit 86 as an on/off command, the purpose of which will be explained later.

The system is completed by a cycle timer 100 fed from the sequencer 71 and feeding a signal PON to the setpoint means 44. The cycle timer determines the signal PON as the time on divided by the time on plus the time off, i.e. $TON/(TON+TOFF)$. This, in effect, tells the setpoint means 44 the fraction of on time in the previous complete on/off cycle.

The setpoint means 44 has two different operating modes that are established by the limit signal LS. If LS is 0, then the output of setpoint means PSET is a function of the manual setpoints PH and PL along with the integrated signal I. If LS is 1, then the setpoint output PSET is a function of the manual setpoints PL and POFF, along with the cycle timer 100 signal PON. These two modes of operation are the crux of the proper operation of the present system and provide a setpoint shifting signal PSET that is differenced with the pressure signal from sensor 41.

OPERATION

A signal can be described as flowing through the system. The output of sensor 41 is differenced at 43 with the setpoint PSET to give the preliminary error signal EP. This passes through the gain element 52 and is limited at 54 to a range of -1 and +1. A signal of 0 is equivalent to a low firefiring rate for a burner, while a signal level of 1 is the highest firefiring rate. Thus, the proportional error from limiter 54 can command the highest firing rate even with the output of the integral action providing an integral signal I of 0. Similarly, a sufficiently large negative proportional error can completely cancel the integrator output.

The output of limiter 54 is fed to summer 62 and also

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enters the integrator 57 to provide an integral action. The output of the integrator 57 is limited at 60 to a range of 0 to 1. The limited integral output I is added to the proportional error from limiter 54 by the summer 62 to provide an actuator command which is limited at 63 to a range of 0 to 1 and then passes through gate 65. If the limit signal LS is high (logic 1), the output of gate 65 is 0, locking the burner for the boiler in the low fire condition during on/off cycling. This function is a derivative action as the limit signal LS is controlled by the rate of change of pressure as described earlier. When the limit signal LS is off (logic 1), the actuator command signal passes unchanged through gate 65, and is converted at 67 into an output signal that is capable of driving a servo motor via the sequencer 71. The sequencer 71 passes this signal unchanged to the servo motor after it has safely ignited the main burner flame.

The signal I is also fed to the setpoint means 44. If the limit signal LS is 0, indicating proportional operation, the setpoint means 44 functions according to the formula given above, to adjust PSET to the low fire value PL when the integrator output is 0 indicating low loads. When the integrator output is 1, PSET represents the need for a high fire setting PH. When the loads range between the high and the low fire operating points, PSET is linearly adjusted automatically between the manually inputted values high fire and low fire settings. In this way the device can be adjusted to automatically raise and lower the setpoint with load. The high fire and low fire setpoints can be determined by trial and error at the actual installation of the burner and boiler. The highest efficiency is obtained when both values are adjusted as low as is practical subject to the requirement of satisfying the end use of loads.

The preliminary error signal EP is also converted to an on/off digital command in the on/off error detection means 51. When the sensed pressure falls to a predetermined

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level below the setpoint, the output of the on/off error detector means 51 switches from off to on. When EP rises to another predetermined level above the setpoint, the output switches back from on to off. The on/off command passes from the on/off error detection means 51 to the sequencer 71 to allow for normal startup of a burner as controlled by the sequencer 71. At the same time the on/off command controls the load responsive means 86 to help determine the limit signal LS.

10 The sensor 41 also feeds the load responsive means 86, which determines the sign of the time rate of change of pressure (that is, determines whether the pressure is rising or falling). Whenever the on/off command signal from unit 51 switches from on to off, the limit signal LS is set to 1.

15 That is, whenever the burner is turned off, it is assumed to be in the cycling mode of operation and the firing rate is locked to the low fire position whenever the boiler and its associated burner restart. When the boiler is turned back on again and begins firing, the limit signal LS will

20 be set back to a 0 if the pressure falls, indicating the load has risen above the lowest firing rate. The fact that the pressure is falling is not meaningful until the fire has successfully ignited and combustion has been underway for an interval sufficiently long to yield a good measure

25 of the rate of change of pressure in the boiler. Typically this takes 60 to 120 s after the firing is initiated. The timer 88 within the means 86 maintains the limit signal LS in the high fire state independent of the rate of change of pressure until the necessary time delay interval has passed.

30 This assures that the startup transients will be excluded from controlling the system. From then on, the limit signal LS remains high as long as the pressure is rising. Whenever the pressure falls, ~~the limit signal LS is set to 0~~ and the modulating operation of the system is allowed. The

35 limit switch signal LS can only be reset back to a 1 if the boiler is turned off again.

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In the setpoint means 44, a different setpoint relationship is utilized when the limit signal LS is 1. Under these conditions, the burner is cycling on and off with the firing rate locked in its lowest position. In this case, the formula is driven by the fraction on time signal PON. The fraction on time signal comes from the cycle timer 100, which measures the time that the fire is on and the time the fire is off during each cycle. The sequencer 17 feeds back a digital signal indicating that the fire has successfully lit up to control the cycle timer 100. The fraction on signal PON is the on time divided by the sum of the on and off times of the previous cycle. During cycling operation, the on and off time intervals utilized in the cycle timer 100 utilize information stored from the most recent cycle. Each time a switching event from on to off or from off to on occurs, the appropriate time value is updated.

When the limit signal LS is 1 the pressure setpoint PSET is equal to the desired standby pressure POFF plus the difference between the desired low fire setpoint PL minus the desired standby setpoint POFF multiplied by the fraction on signal PON. The standby pressure is the desired condition when the load has fallen to zero. This would be the hot standby condition of the boiler. When the fraction on signal is 0, the setpoint is the standby setpoint. When the fraction on signal rises to 1, the low fire setpoint is utilized. The setpoint means 44 automatically adjust the setpoint between these manually inputted levels with load variation. In this way the setpoint of the system is automatically adjusted with load to its minimum allowable value during the modulating operation (with the limit signal LS at 0) and the cycling operation (with the limit signal LS at 1).

The limit signal LS also controls the make to break differential means 94, which determines the pressure level at which the on/off command signal is switched. When the burner is in the cycling mode the make to break differential MTBD is left at the level of the manual input to the

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system. The operator can adjust the make to break differential to constrain the amplitude of pressure variations during the on/off cycling. When the make to break differential is small, the boiler cycles rapidly between the highest and lowest pressure levels. When the make to break differential is larger the boiler cycles more slowly with a large pressure amplitude. When faster cycling occurs, greater cycling losses and less efficiency occur. Slower cycling is more efficient but the pressure amplitude is greater. The operator can determine the acceptable level of cycling. We have found that it is desirable to use a larger make to break differential when the boiler is operating in a modulating mode (that is with the limit signal LS at 0). During modulating operation the sensed pressure will remain near the setpoint value as long as the loads remain relatively steady. As the load changes abruptly, the pressure will drift off of the setpoint until the control system can adjust the firing rate and reestablish equilibrium conditions. If the break level is too close to the setpoint during modulating operations, an abrupt load drop of a few percent can cause pressure to rise to the break level before the proportional control loop can readjust the firing rate. Under these conditions unnecessary on/off cycling can occur. To prevent this, the make to break means 94 is operable with two ranges and is operated in the expanded range during the modulating operation so that the pressure must rise significantly above the setpoint to switch off the burner. This eliminates unnecessary cycling, and improves stability and thereby saves energy.

The present system utilizes two interrelated concepts. The first is the derivative action technique which limits the firing rate to its lowest level during on/off cycling. The limit signal output also indicates whether the boiler is in the cycling mode or the modulating mode of operation. This information is necessary to utilize the fraction on or the integrator output as a measure of load on the system.

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With this measurement of load, it is possible to reset the setpoint means 44 thereby maintaining the lowest possible temperature and hence highest efficiency operation possible under varying load conditions. The reset concept must include some type of load responsive means to determine the direction that the temperature or pressure is varying.

MICROCOMPUTER VERSION

An equivalent of the Figure 3 system can readily be provided by a microcomputer, with all of its functions being entered in the program. The resulting system is a single input, dual output control. The system senses boiler pressure or temperature and controls the on/off switch to the sequencer 71 and the firing rate control signal. The system has two internal states, modulating and cycling. The cycling state consists of on/off cycling with the firing rate locked in the lowest firing rate position. The setpoint is adjusted with load by timing the on/off cycle durations and adjusting the setpoint means accordingly. The device is in the cycling mode whenever the load on the boiler is less than the lowest possible sustained firing rate. The system enters the modulating mode whenever the loads are higher than the lowest possible sustained firing rate. In modulation, the boiler is continuously on and the firing rate is varied between the lowest and highest firing rates possible, and integral action is utilized to eliminate the proportional offset between the pressure and the setpoint in steady state. The output of the integral action is also used to reset the setpoint with load variations. Internal to the system, seven control parameters must be retained in memory. These parameters are, the control mode LS (cycling or modulating), the output switch state, the firing rate command, the output of the integral action integrator I, the timed duration of the most recent complete firing cycle (on time), the most recent complete off cycle duration (off time), and the duration of the present half cycle.

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OVERALL PROGRAM

The overall program will be described first, and several functions in it will then be described in more detail.

5 The overall program consists of several functions 105 to 121 forming an endless loop, with a branch in the loop for modulating or cycling mode, and with an initial entry path. The functions follow each other in sequence unless otherwise stated.

10 105: to start the program, this block initializes certain parameters. The mode is set to cycling with the output switch off, firing rate to minimum, the integral action value to zero, the stored on and off times to maximum and minimum respectively, and the cycle timer to zero. Thus, the system starts with the boiler off and cycling under way. The internal setpoint will be
15 adjusted to that for low fire loads.

106: this is the return point for the endless loop.

107: read inputs. The inputs are the pressure from the pressure sensor, the manual inputs PH, PL, and POFF, and the make to break differential.
20

108: is the controller in the cycling or modulating mode? The cycling functions (110 to 113) or the modulating functions (116 to 121) follow accordingly.

114: pass the output firing rate and switch state command to the actuating means. This turns the boiler on or off, if required, and adjusts the firing rate appropriately.
25

115: increment the cycle timer, and return to 106.

Cycling function sequence 110 to 113.

30 This is as follows:

110: compute the setpoint and make to break levels.

111: cycling logic. This compares the pressure value with the make and break points to determine the proper output switch state.

35 112: mode control logic. This determines whether the burner is on and the pressure falling; if so, the system

- 20 -

must change to the modulating state.

113: on/off timer logic. This controls the timing of each cycle and updates the stored values of the most recent complete on and off half-cycles.

5 Modulating function sequence 116 to 121.

This is as follows:

116: compute the setpoint and break levels.

117: compute the proportional and integral gains. These must be adjusted for the amount of pressure reset commanded by the operator and the pressure range of operation, and they constitute automatic gain adjustments assuring stable operation with consistent dynamic response under all operating conditions.

118: compute the proportional and integral errors, and thence the firing rate command.

120: increment the integral action integrator by 1 time step.

121: test boiler for shut-off. This compares the pressure value with the break level; if the pressure exceeds the break level, the boiler is switched off and the mode changed to cycling.

The functions of the cycling function sequence will now be described in detail.

110: compute cycling setpoint, make and break levels

25 This consists of four sequential subfunctions.

1. Compute PON as $TON/(TON + TOFF)$, where TON and TOFF are the stored on and off times.
2. Compute the setpoint PSET as $POFF + (PL - POFF)PON$, where POFF and PL are manually entered standby and low fire setpoints.
3. Compute the break level as PSET plus the manually entered make to break differential.
4. Set the make level as PSET.

111: cycling logic

35 This subfunction tests the pressure level, and (a) turns the firing switch on if it is off and the pressure is

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below the make level, and (b) turns the switch off if it is on and the pressure is above the break level.

112: mode control logic

5 This subfunction performs one of three sets of operations A, B, and C, depending on the results of various tests. The first two tests are (1) is the fire on or off?, and (2) are the cycle timer contents greater than the minimum wait time? If the fire is off, or the cycle timer contents are too low (indicating that the boiler has not been on for long enough to establish a valid trend), operations A are performed.

A: keep the mode in cycling, set the integrator to zero, and set the firing rate to the minimum value FL.

15 If the fire is on and the cycle timer contents are large enough, there follows a test (3), is the pressure above the minimum possible sensor reading? If it is not, the pressure is below scale, and operations B are performed.

B: keep the mode in cycling, set the integrator to zero, and set the firing rate to the maximum value FH; this is to bring the pressure back into the sensor range as quickly as possible.

20 If, in test (3), the pressure is above the minimum sensor reading, then two further tests follow: (4) is pressure below the make level? and (5) is the pressure falling? If the pressure is not below the make level, or if the pressure is not falling, operations A are performed. Otherwise, operations C are performed.

C: change the mode to modulating, set the stored on and off times to maximum and zero respectively, and set the cycle timer to zero.

30 In the cycling mode the firing rate command is normally fixed to the minimum value. The only exception to this rule is if the pressure is below the minimum possible sensor reading, and the fire has been on for longer than the minimum time (typically 60 to 120 s) needed to establish a valid pressure trend. Under these conditions, the maximum firing

- 22 -

rate is allowed. This will always bring the pressure back into the sensor range with the mode in the cycling state. Once the pressure rises above the bottom of the sensor range, the firing rate is driven back to its minimum value.

- 5 If the pressure falls as a result of this action, the sensor can detect the downward pressure trend after the pressure has been driven back into the sensor range. The downward pressure trend is interpreted as a need to switch to the modulating mode, which allows steady higher firing rates.
- 10 It is hoped that a sensor with adequate range can always be utilized to prevent the pressure from ever falling below the bottom of the scale. This extra mode of operation is a backup condition, should such a sensor prove not to be available.

15 113: on/off timer logic

- This subfunction starts by determining whether the firing switch, which was controlled in subfunction 111 (cycling logic), changed state in that subfunction. If it did, then the cycle timer contents are loaded into the off time (if
- 20 the switch changed from off to on) or the on time (if the switch changed from on to off) storage, and the cycle timer is reset at zero. Also, the output switch is set to match the current state of the firing switch.

- Next, the stored off time is updated from the cycle
- 25 timer if the fire is off and the cycle timer contents exceed the current stored off time, or the stored on time is similarly updated if the fire is on and the cycle timer contents exceed the current stored on time. The on and off times are used to compute the apparent load on the boiler.
- 30 If the load is rising, for example, each successive on time interval will be longer than the previous one. As soon as the on time in the cycle timer gets longer than the stored previous value we can correctly deduce that the load has risen. Thus, the stored on time is updated continuously
- 35 after the cycle timer gets greater than the stored value. If however the load is falling, the stored times cannot be

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updated until switching occurs.

The functions of the modulating function sequence will now be described in detail.

116: compute modulating and setpoint levels

5 This consists of two sequential subfunctions.

1. compute PSET as $PL + (PH - PL)I$, where PL and PH are manually entered and I is the integrator value.
2. compute the break point as PSET + a predetermined fraction of the sensor range. Since the boiler is already firing in the modulating mode, a make point associated with modulating control is not required. The break point formula could employ the manual make to break differential. However, abrupt load changes would cause the pressure to vary from setpoint during modulating control by an amount greater than the normal make to break differential. Thus, to enhance stability and prevent unnecessary cycling, the manual input is overridden by a fixed percentage of the sensor range. This higher break point will only be utilized when the loads fall below the throttling range of the burner for a sustained period requiring burner shutdown. This happens perhaps daily during some seasons of the year, but no more frequently than that. Thus, this modification should be invisible to the user.

25 118: firing rate control

The first subfunction of this function is the calculation of the proportional error:

$$EP = (PSET - \text{pressure value})K_p,$$

where $1/K_p$ is the throttling range. EP is then limited if it is outside the range 1 to -1. If it has to be so limited the input to the integrator is set to zero; otherwise, the input to the integrator is set to $EP.K_i$, where K_i is the integral gain. The firing rate command is then calculated, as the sum of EP and the integrator output.

35 Since the integral output can range as high as +1, it is desirable to allow the proportional gain to range as low

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as -1 to achieve a net firing rate command of zero when necessary under dynamic load changes. The input to the integrator is normally the integral gain multiplied by the proportional error. If the proportional error is outside its allowed range before the limiting functions, a dramatic load change event must have occurred. Under these conditions, it is not desirable to allow the integrator to "wind up" to a large value during the transient period. Thus, the integrator input is set to zero when the proportional error is outside its normal range.

The firing rate command is converted to the appropriate analog signal for driving the actuators. The integrator output is limited to the range from 0 to 1. Thus, under some conditions the sum of the proportional error plus integral output may be greater than the highest firing rate command possible or less than the lowest firing rate command possible. The digital to analog conversion must effect a limit function in such a way that the actuators are actually driven to either extreme position when the command is outside the limit.

120: integral action

In this function, the integral output value is updated by incrementing it with the product of the cycle time increment and the input to the integrator, as calculated in function 118.

121: test for boiler shut-off

This function determines whether the boiler is to be shut down; if it is, the mode changes to the cycling mode. The function begins with three tests. If (a), the fire is on, (b) the pressure is below a fixed maximum level, and (c) the pressure is below the break level, then the system remains in the modulating mode. There are many safety interlock controls which can shut the boiler down for reasons other than steam pressure. If one of these other shutdown events occurs, the system must conform with that event. The fixed maximum allowed pressure level may be the upper

- 25 -

limit of the pressure sensor range.

However, if any of these criteria is not met, then the system changes to the cycling mode. This is achieved by turning off the fire switch, setting the integral output to zero, setting the stored on and off times to the maximum and minimum values respectively, setting the mode to cycling, and setting the firing rate command to the minimum value. In this way, when the control begins cyclic operation, the long on time causes the setpoint reset subfunction in the cycling mode to command a setpoint equal to the low fire setpoint value. Thus, in the case of a gradual drop in load, the modulating control will reset the setpoint down to the low fire value and cycling operation will begin from that setpoint level. This ensures a "bumpless" transition from one mode to another.

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CLAIMS

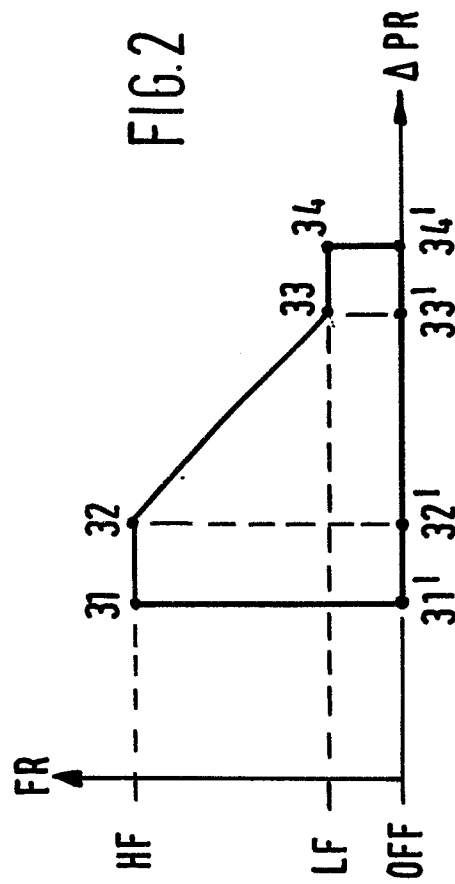
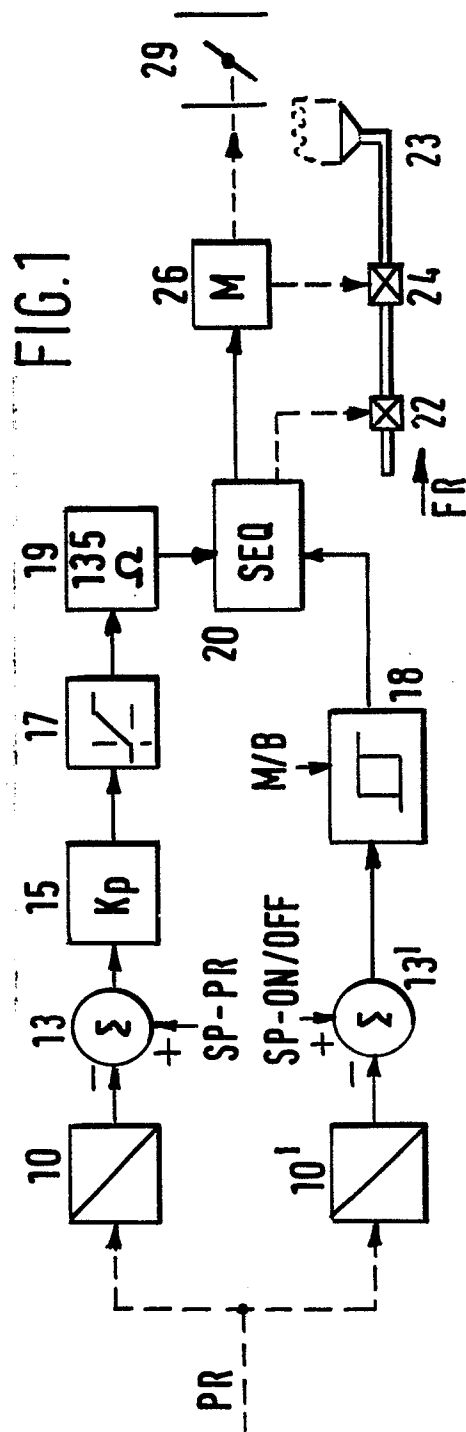
1. A control system for a boiler or the like wherein an on/off control signal and a proportional control signal are generated in response to a sensed condition value, characterized by mode control circuitry (86), which, when the system is in the cycling mode (LS = 1), holds the firing rate of the boiler to the lowest rate (LF), and changes the mode to proportional (modulating) if the sensed condition value falls while in the cycling mode.
2. A control system according to Claim 1, characterized in that the sensed condition value is differenced with a setpoint value (PSET) to form a proportional error signal (EP), and by an integral action integrator (57) the output of which is combined with the proportional error signal to form the proportional control signal and is used (at 44) to adjust the setpoint value in the modulating mode.
3. A control system according to either previous Claim, characterized in that the duty ratio (PON) of the cycling is used to adjust the setpoint signal in the cycling mode.
4. A control system according to Claims 2 and 3, characterized in that the setpoint signal is determined in dependence on manually entered low fire (PL), high fire (PH), and off (POFF) rates.
5. A control system according to any previous Claim, characterized by switching means (65) for passing the proportional control signal to the boiler and controlled by the mode control circuitry.
6. A control system according to any previous Claim, characterized in that the sensed condition is pressure.
7. A control system according to any previous Claim, characterized in that the means (51) for generating the on/off control signal has the width of its differential

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band adjusted (by 94) in dependence on the operating mode
(signal LS).

1/2



2/2

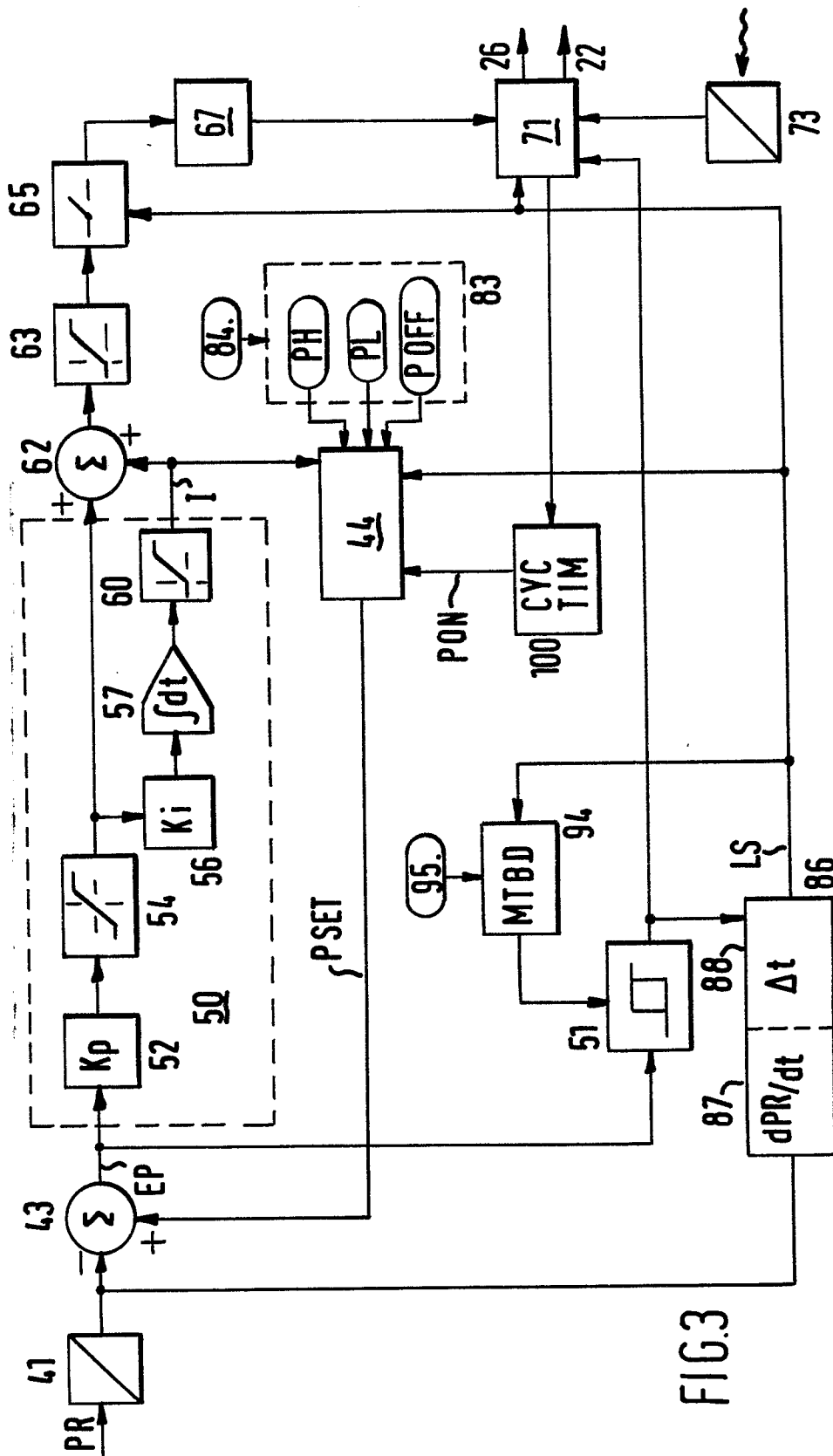


FIG. 3